THE RADOME DESIGN OF L-BAND SATELLITE TRACKING VEHICLE ANTENNA

Innovative material selection and sealing reinforcement

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Mechanical Engineering, Bachelor's thesis

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Examiner: Professor Tapio Saarelainen

ABSTRACT

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This thesis focuses on designing the radome of a L-band satellite tracking vehicle antenna. It identifies the optimal materials which offers the best balance between dielectric properties and environmental resistance. Innovative sealing solutions are also discussed. By comparing modern polymers with traditional materials like fiberglass, it aims to enhance performance and extend the lifespan of the radome. Applying a mixed-method approach, combining DFMA analysis and systematic material selection, the study finds acrylic and nanocomposite sealants as superior choices for radome construction and sealing. These selections promise improvements in the radome's efficiency and longevity. It is critical for maintaining high-quality satellite communications.

ACKNOWLEDGEMENTS

I would like to express my sincerest thanks to my supervisor, Tapio Saarelainen, for his unwavering support and valuable recognition throughout my research. His profound mentorship and enlightening perspectives in radar design, coupled with his significant contributions to the relevant source of literature, have been instrumental to my investigation. I am deeply appreciative of the educational guidance afforded by the university and faculty, which has been pivotal in the refinement of my academic pursuits.

The topic of this thesis belongs to the broader research project at LUT University during year 2024. The research project focuses to the DFMA and sustainability analyses of more than 40 different MW and RF components. The results of this thesis will be utilized later to build an overall picture of the DFMA and sustainability aspects related to MW and RF technology.

SYMBOLS AND ABBREVIATIONS

Φ_S	Contact Angle
λ_r	Radome Error between apparent target and true target
γ_{GS}	Gas – Solid Interfacial Tension
γ_{LS}	Liquid – Solid Interfacial Tension
γ_{LG}	Liquid – Gas Interfacial Tension
ABS	Acrylonitrile Butadiene Styrene
AC	Acrylic
CAM	Computer-aided manufacturing
CNC	Computer Numerical Control
DFMA	Design for Manufacturing and Assembly
EMC	Electromagnetic Compatibility
EVA	Ethylene Vinyl Acetate
GHz	Gigahertz
GRP	Glass Reinforced Plastic
MMT	Montmorillonite
PC	Polycarbonates
PE	Polyethylene
PI	Polyimide
RF	Radio Frequency
RTV	Room Temperature Vulcanizing Silicone
SiO2	Silicon Dioxide
UAV	Unmanned Aerial Vehicles
UV	Ultraviolet Light

Table of contents

1 Introduction

1.1 Objective and research problem

The aim of this research is to improve satellite communication technology by identifying innovative materials and sealing techniques for the radome of an L-band satellite tracking vehicle antenna. The research also includes optimising the performance and lifetime of the radome in the face of increasing demand for reliable and efficient data transmission.

This leads to the research problem:

What materials offer the best balance between dielectric properties and environmental resistance for use in L-band radomes?

How do innovative sealing solutions contribute to the radome’s durability and operational reliability?

What are the comparative advantages of modern polymers or composites over traditional materials like fiberglass in the context of radome construction?

1.2 Research methods and expected outcomes

In this study, a mixed approach is used to optimise the material and sealing method for the radome of an L-band satellite tracking vehicle using a combination of literature review, systematic material selection based on dielectric properties and environmental resistance.

The expected outcomes of this research include:

Identification of an optimal material for the radome that offers superior dielectric properties, environmental resistance, and is conducive to manufacturing processes.

Development of innovative sealing solutions that enhance the radome's durability and operational reliability.

2 Literature review

2.1 Requirements of materials for antenna radome

2.1.1 General requirements of antenna radome

In order to clarify the basic requirements of the radome, it is necessary to understand the basic definitions of the radome as well as its functions in enhancing wireless communications. Radome is a synthetic word that stands for radar and dome. It is a rugged enclosure that protects the antenna and can support all-weather use[3]. The material of the radome enclosure has low attenuation, which allows the antenna inside the radome to transmit or receive complete electromagnetic signals[5].

Figure 1. External structure of a radome[52].

The radome has multiple functions. On the one hand, it can guarantee the smoothness of radio wave transmission and the integrity of the wave band. At the same time, it has the ability to resist the interference of extreme weather environment, such as extreme dry or humid severe weather. On the other hand, the radome is structurally protective and hides the inherently sensitive electronic equipment. It avoids passing personnel from being injured by fast moving antennas.[8]

This paper identifies specific requirements for radomes in three areas: electrical transparency, structural integrity, and mechanical durability. These three criteria help the radome to

operate properly and perform optimally, in terms of receiving and transmitting electromagnetic signals and withstanding the mechanical and physical stresses imposed by the operational environment.[1]

2.1.2 Specific requirements of materials for tracking vehicle antenna radome

Antennas used in transport applications often have higher requirements than normal antennas, for example on trucks and ferries. Firstly, in terms of structural design, the radome should have an aerodynamic shape that is more suitable for the movement of the transport vehicle, in order to reduce the aerodynamic resistance of the radome during the movement[6]. As Figure 2 shows, this design not only reduces the displacement deviation of the transport vehicle due to the lift force during travelling, but also reduces the negative impact on vehicle speed and fuel consumption efficiency.[11]

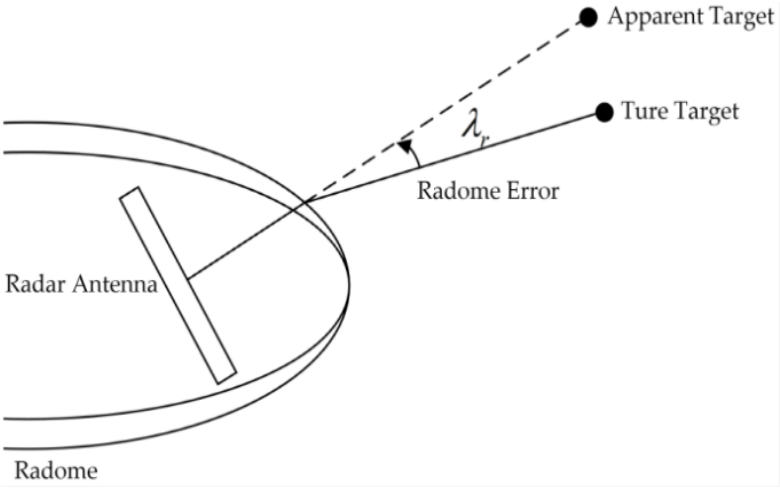


Figure 2. The radome is required to protect the radar antenna from air flow[30].

Secondly, the materials used for radomes in the transportation sector should have good physical properties, with emphasis on abrasion and impact resistance. The radome must be able to withstand the extreme conditions of the working environment, such as rain and sand erosion[42].

Another perspective of selecting tracking vehicle antenna radome material is to consider its protection of the internal antenna, because the high gain directional antenna plays a major role in the overall radar system. It may have influence on the precise positioning of the

intended target. The system is commonly used for fast moving objects (e.g. UAVs) that need to be tracked. Nugroho, G. and Dectaviansyah, D. (2018) in their study found that the integration of such tracking systems requires a radome that not only protects the antenna, but also does not interfere with the antenna's ability to adjust and maintain its directional focus on a moving object.[2][17]

2.1.3 Reasons why the L-band satellite tracking vehicle antenna has high material requirements

The L-band operates between 1 GHz and 2 GHz and is a widely used frequency band for satellite communications. The antenna is compact in size and provides efficient signal propagation. This frequency range provides an optimal solution for long distance communications. Satellites are guaranteed to transmit electromagnetic information and signals quickly, efficiently, and completely.[10]

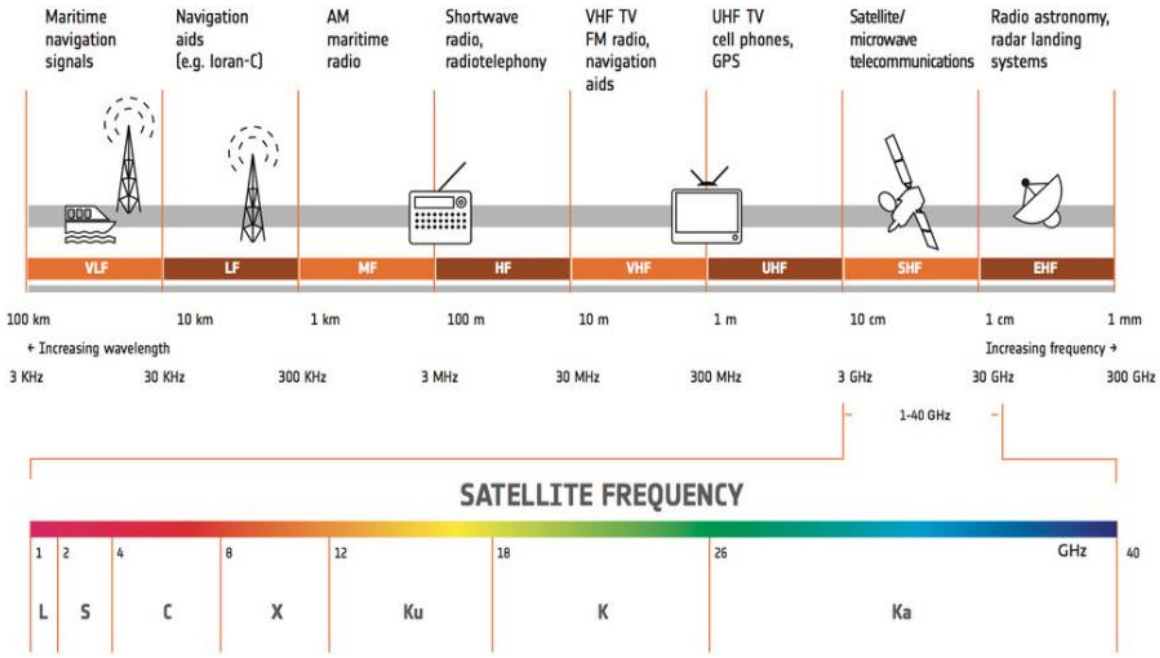


Figure 3. Satellite frequency bands[53].

Signals in the L-band frequency can play an important role in special tactical operations and search and rescue missions, as it responds to global communication needs at low frequencies. Its longer wavelength allows it to easily pass through obstacles such as buildings, mountains

and other obstructions that interfere with the high frequency band. The penetration of this band contrasts with the limitations of higher frequencies such as the Ku and Ka bands. The latter, due to their shorter wavelengths, are more susceptible to being blocked by solid obstacles[4][31]. This leads to real-world phenomena such as 'rain fade', where signal quality is attenuated and degraded by weather conditions[13].

However, L-band offers a more reliable and secure application than higher frequency bands due to its stable performance in bad weather. It can even cover the global domain with stable operation. In particular, in response to rain and other climatic factors, L-band still has the ability to maintain broadband stable communication to protect the integrity of the signal in long-distance communication[32]. Particularly in the conduct of strategic operations and search and rescue missions, L-band signals can ensure uninterrupted communication needs and contribute to the success of these operations[20].

Based on the high efficiency and functionality of L-band antenna, the radome requirements can be even more strict according to the requirements in 2.1.1 and 2.1.2.

2.2 Cause of sealing problems and previous research examination

2.2.1 Introduction to causes sealing problems and sealing processes

Typically, when considering radome sealing problems, improper use of sealants and improper selection of radome materials can lead to radome sealing problems[33]. Once a sealing problem occurs, the radome's ability to withstand harsh environments such as moisture and corrosion is reduced[34].

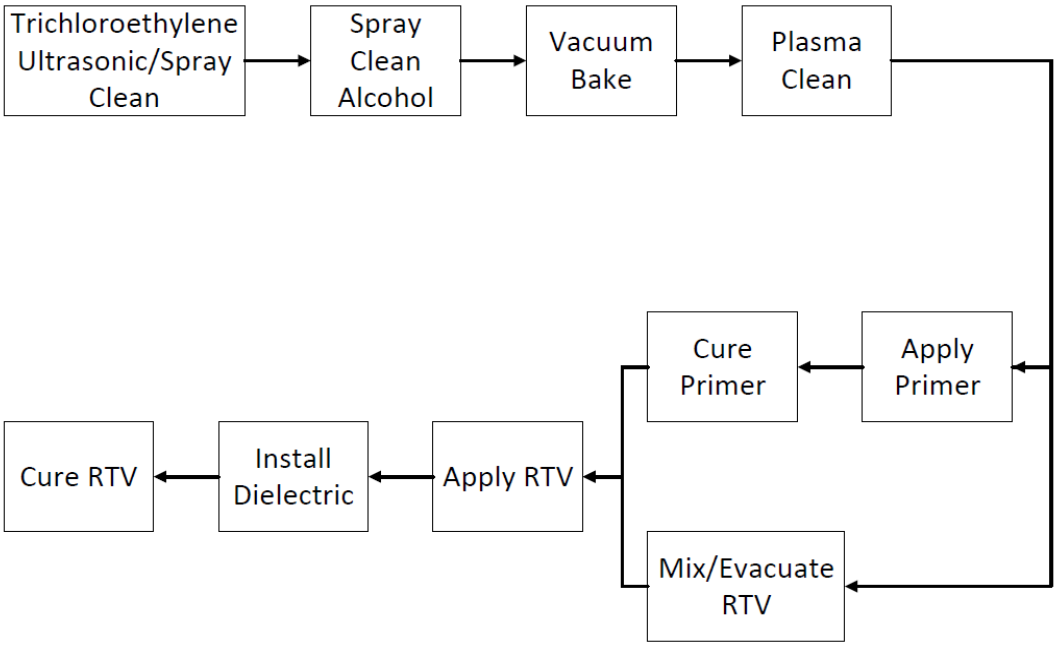


Figure 4. Current dielectric sealing process steps[7].

In 1994, Busby M.L. and Yerganian S.S. examined key factors affecting antenna sealing efficiency, especially the interaction of RTV silicone adhesive with primer. They found that alterations in primer composition and insufficient curing times adversely affected the adhesive's bonding strength between the dielectric and antenna housing, a vital aspect for antenna reliability and moisture prevention, as outlined in their process in Figure 4.[7]

The potential causes of sealing problems are illustrated in the cause and effect diagram Figure 5, emphasizing the necessity for attention to detail in the selection and application of materials in antenna manufacturing.

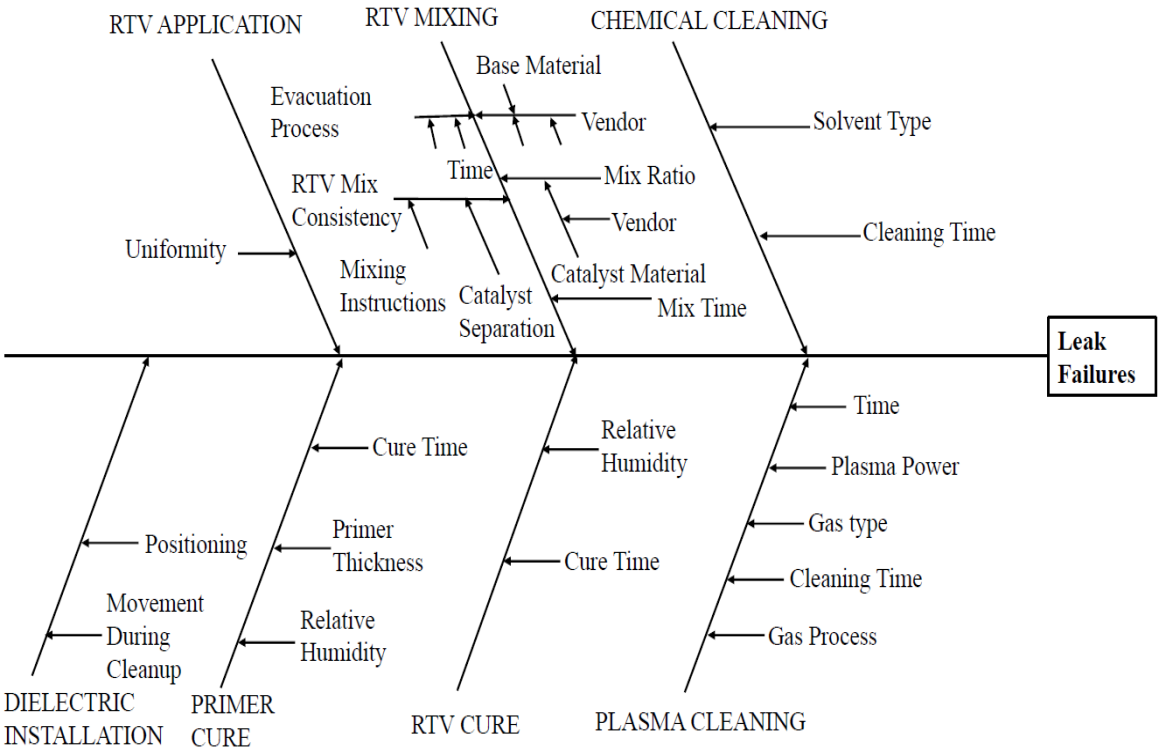


Figure 5. Cause and effect diagram of variables that can affect yields[7].

2.2.2 Metal closure mechanism for radome watertight integrity

The radome watertight closure mechanism described in a previous research presents an innovative solution to ensure the integrity and watertightness of radomes, particularly in high-pressure environments such as maritime and submarine applications.

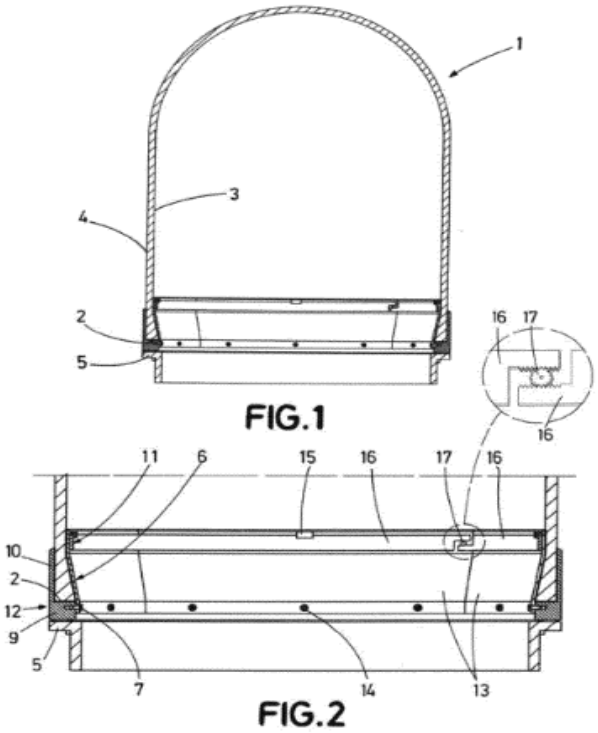


Figure 6. Metal material closure mechanism[22].

In the 2021 study by PIPÓ BENITO and Alvaro, they focus on a metal material closure mechanism designed to enhance radome integrity. This mechanism comprises four key components: an outer ring, an inner ring, a connecting base, and pressure and closing elements. These elements work together to securely fasten the radome around its lower edge, creating a watertight seal. Such an approach can not only maintains the radome's structural integrity but also effectively improve radome watertightness.[22]

3 Methods

3.1 DFMA guidelines

Design for Manufacturing and Assembly (DFMA) is a set of principles aiming at simplifying the design of a product. This helps make manufacture and assembly easier and more cost-effective[12]. The design involves minimizing the number of parts and designing for ease of assembly as well selecting materials that streamline the manufacturing process while maintaining functionality and quality[35][36]. Figure 7 shows the typical DFMA procedure.

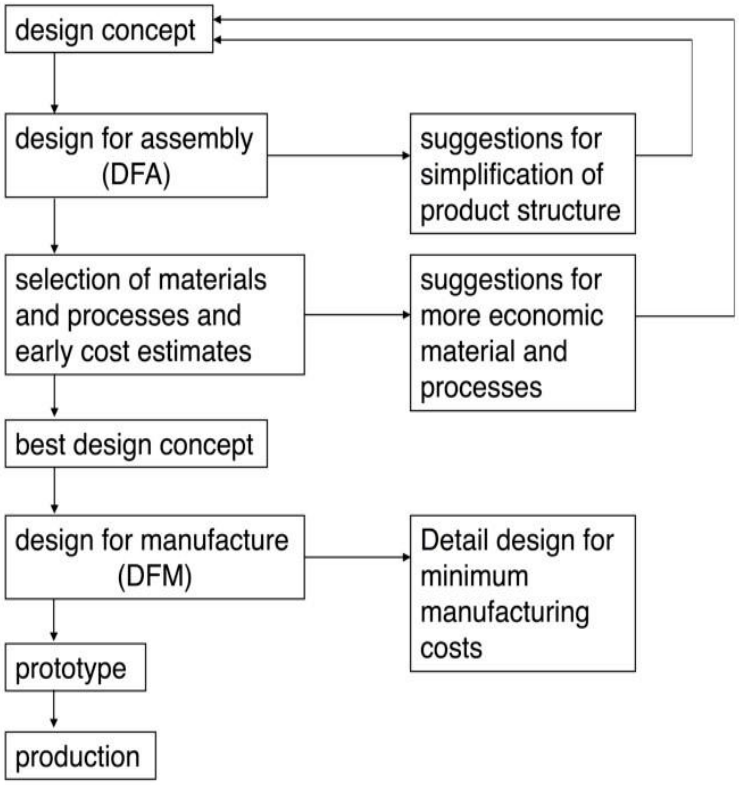


Figure 7. Steps for DFMA methodology[37].

3.2 Systematic material selection

Figure 8 shows how to proceed systematic material selection when choosing the material for radome. Firstly, the procedure involves selecting materials from two types materials,

traditional materials and modern materials. One candidate material will be selected from each type. Then it follows that the comparison of these two candidate materials. After that, a thorough analysis will be conducted to discover which one is more suitable to be the radome material.[23]

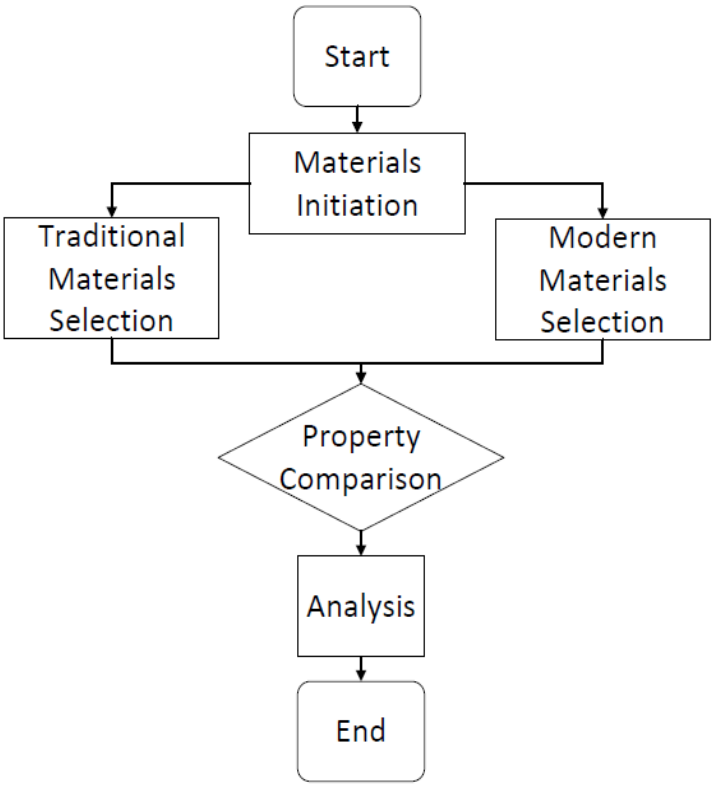


Figure 8. Systematic material selection process.

3.2.1 Fiberglass as a traditional radome material

Fiberglass, or glass-reinforced plastic (GRP), stands out as the preferred material for L-band satellite tracking vehicle antenna radomes, because of its outstanding electrical transparency, structural integrity, and mechanical durability[1]. From electrical transparency perspective, it has a low dielectric constant and minimal dielectric loss[38], ensures minimal interference with satellite communications. Structurally, fiberglass withstands physical stresses like impacts and vibrations resulting from its high strength-to-weight ratio and stability[39][40]. Its resilience against environmental factors such as temperature fluctuations, moisture, UV

radiation, and corrosion[26], due to its robust composition and manufacturing, extends the radome's lifespan and minimizes maintenance.

3.2.2 Modern radome materials selection

Modern radome materials research is focused on self-healing materials that can repair minor damages, ensuring the radome maintains its integrity over time[27]. These advancements aim to optimize radome functionality for increasingly sophisticated communication systems. Modern polymers or composites perform well such as ABS, PC or PI.

3.3 Design for solving sealing problems

3.3.1 Several aspects to consider

It is also important to optimize the radome and sealing system design to guarantee a snug fit and comprehensive coverage. This optimization may involve the creation of custom gaskets or the incorporation of multiple sealing mechanisms. Design features such as overlapping joints, tongue and groove configurations, and double-sealed edges play a pivotal role in enhancing the radome's sealing capabilities.[28]

The application of advanced sealing technologies offers further improvements in sealing efficacy and functionality. Conductive gaskets can be employed to ensure electromagnetic compatibility (EMC). Breathable membranes can allow pressure equalization, preventing moisture buildup inside the radome.[44]

3.3.2 Detailed material consideration inspired by other industry

One previous research in aerospace industry is crucial for understanding how sealants contribute to preventing moisture ingress and corrosion, as well as supporting cyclic loads to enhance fatigue strength. Of particular interest is the application to radome sealing, where

the challenge lies in ensuring weather resistance without compromising the electromagnetic properties essential for L-band signal transmission.[14]

This research sheds light on various factors influencing sealant selection for radome applications. It notes the importance of the sealant modulus, where high-modulus adhesives such as epoxies are lauded for their strong joints and reduced stress concentrations, in contrast to low-modulus, rubber-like sealants that offer greater flexibility.[14]

An essential finding from another study is the role of a sealant layer in significantly increasing the fatigue life of riveted lap joints by mitigating stress concentrations and bending stresses, a consideration paramount for the radome of a satellite tracking vehicle antenna subjected to dynamic stresses[30]. Additionally, the study emphasizes the necessity for the sealant to withstand environmental and operational factors typical of radome applications, such as UV exposure, temperature variations, and mechanical stresses induced by vehicle movement.[27]

Based on these insights, the study concludes that the ideal sealant for a radome on an L-band satellite tracking vehicle antenna should not only ensure non-interference with L-band signals through a low dielectric constant and loss tangent but also balance structural integrity with flexibility. [14][37]

4 Result

4.1 Acrylic as the material enhancing radome performance

Based on the method discussed in 3.2 which is systematic material selection, the acrylic (AC) is a preferred material for constructing a radome for an L-band satellite tracking vehicle antenna system. Initially, the focus is on achieving a lightweight design to minimize the load on the vehicle, where acrylic stands out for offering a commendable balance between weight and structural integrity, despite not being the lightest option available. This balance is crucial for vehicle-mounted systems where excessive weight could impede functionality.[46]

Acrylic displays lower dielectric constant and loss tangent compared to other materials like fiberglass[51]. This characteristic is pivotal for L-band frequency operations, where signal transparency is paramount; acrylic's lower dielectric constant minimizes phase shift in transmitted signals, thus preserving antenna performance.[12]

Mechanical strength is also a significant factor, and while acrylic may not rival the strength of materials such as silicon nitride, it provides sufficient robustness for the operational conditions expected of a vehicle-mounted system. This level of strength ensures the radome's durability without necessitating the extreme structural strength some other materials offer.[47]

Finally, an analysis of reflectivity at different thicknesses reveals that acrylic offers consistent performance across various incident angles. This consistency is crucial for ensuring uniform transmission of L-band signals, with thinner constructions of acrylic showing lower reflectivity, which is advantageous for signal clarity.[3][48]

4.2 SolidWorks models and technical drawings of the radome

4.2.1 Radome assembly presentation

Figure 8 and Figure 9 clearly present the radome assembly in SolidWorks and the technical drawing of it.

Figure 9. Radome SolidWorks modelling.

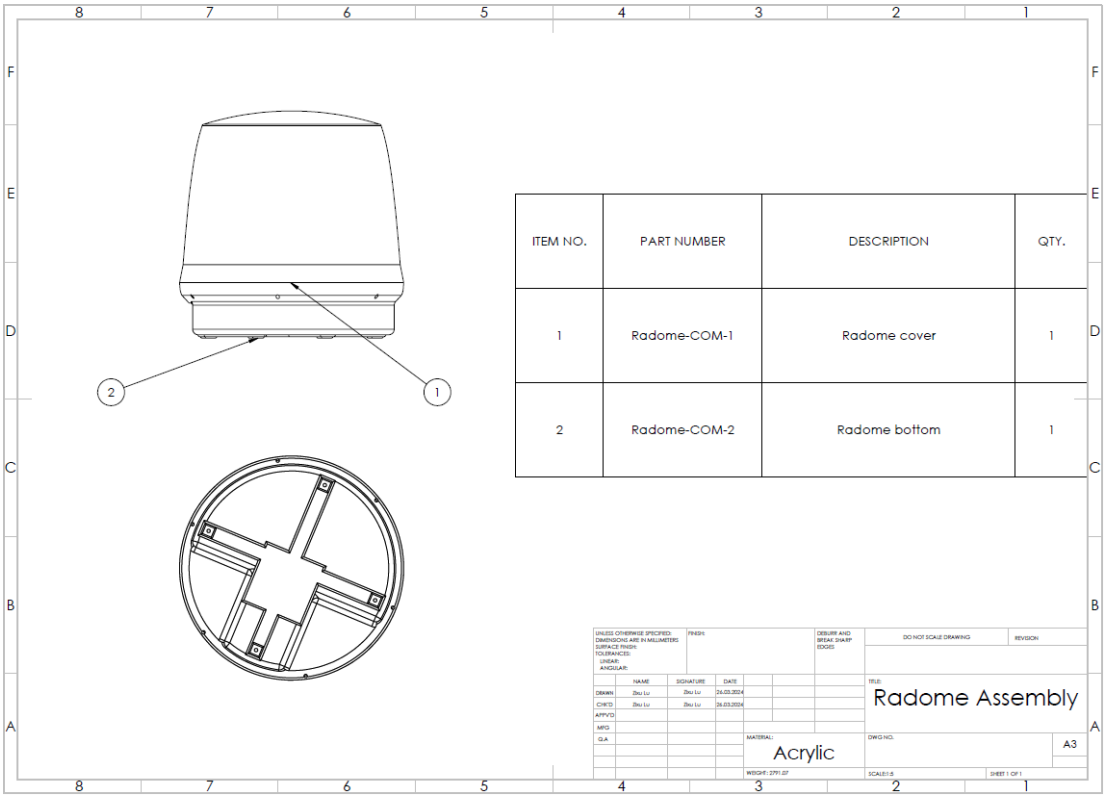


Figure 10. Technical drawing of the radome.

4.2.2 Radome cover and radome bottom presentation

The presentation of radome cover is shown in Figure 10. Figure 11 is the technical drawing of the radome cover which includes detailed presentation of a specific part as well as measurements, geometric tolerances and surface finishes indicated.

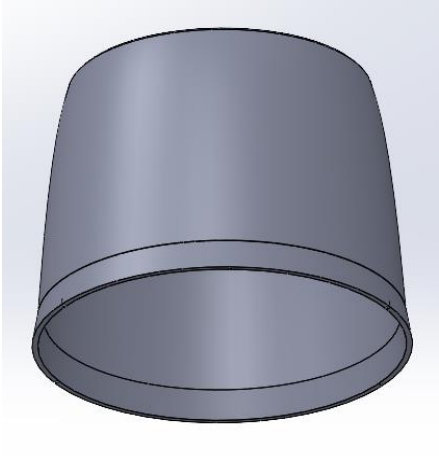


Figure 11. Radome cover SolidWorks modelling.

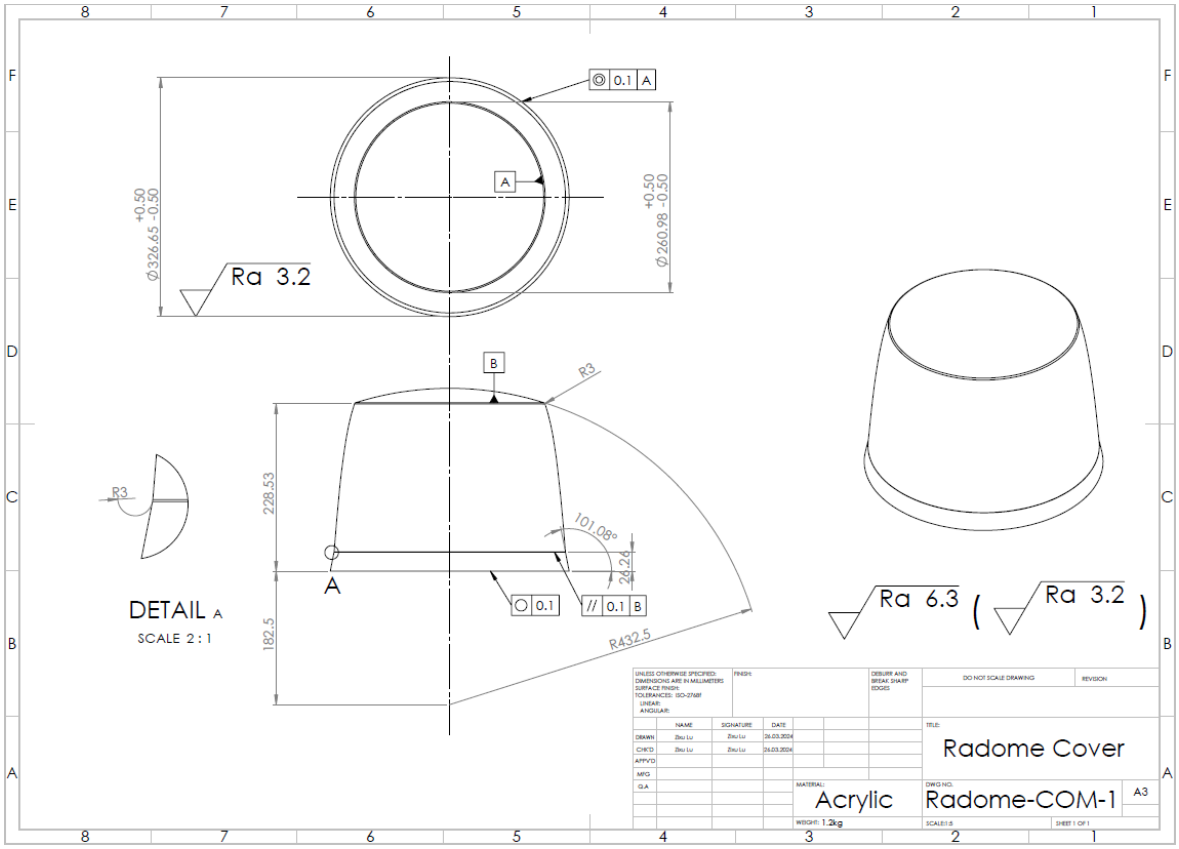


Figure 12. Technical drawing of the radome cover.

From geometric perspective, the radome bottom is a bit more complicated than radome cover, which means a more detailed technical drawing is necessary. Compared to the previous technical drawing, there are section view and datum as a closer presentation. To give a clear presentation, there are two technical drawings for this part.

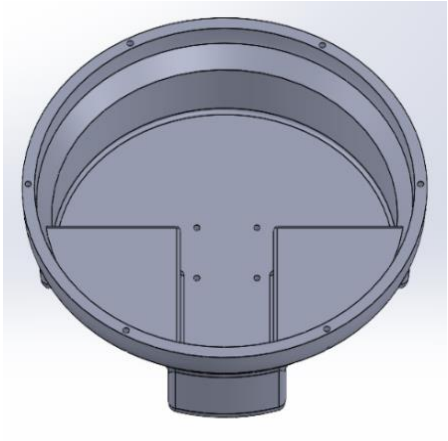


Figure 13. Radome bottom SolidWorks modelling.

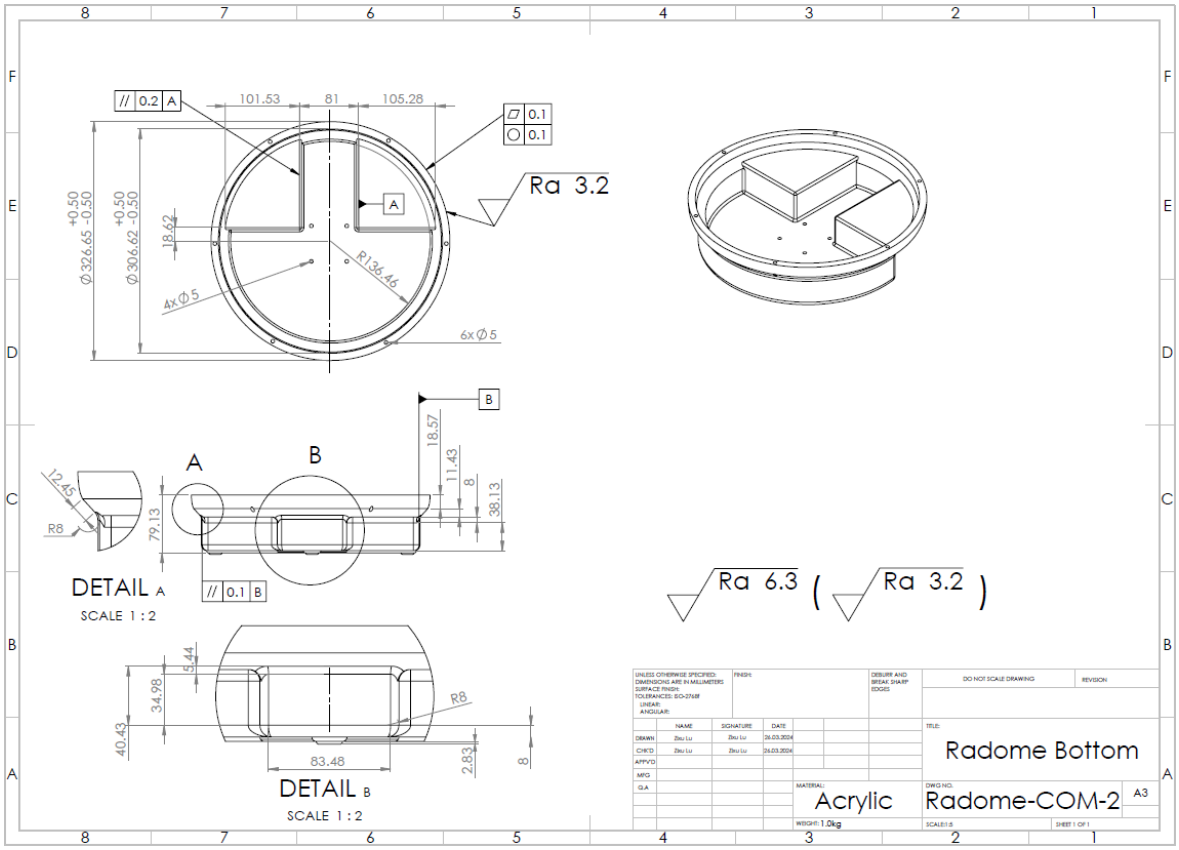


Figure 14. The first technical drawing of the radome bottom.

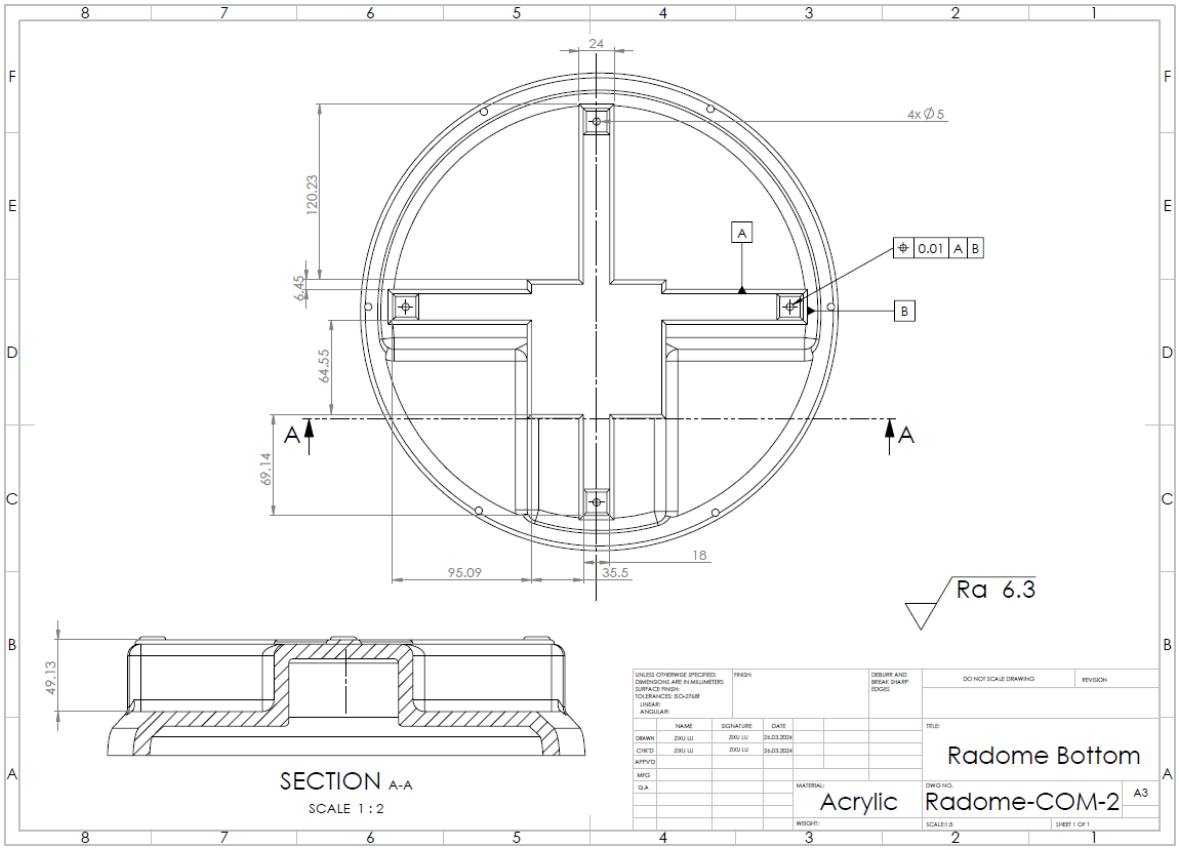


Figure 15. The second technical drawing of the radome bottom.

4.3 Detailed presentation of the sealing solutions

4.3.1 Nanocomposite Sealants selection

Nanocomposite Sealants can enhance traditional sealant materials by incorporating nanoparticles to improve mechanical properties, thermal stability, and resistance to chemical and UV degradation. The paramount consideration in the exploration is ensuring the sealant does not adversely affect the antenna's performance by altering the radome's dielectric properties, a crucial aspect given the radome's role in protecting the antenna system while ensuring minimal signal transmission interference.[29][33]

A significant breakthrough in this field is highlighted by research conducted in 2009 by Manias, E., Zhang, J., Huh, J.Y., Manokruang, K., Songtipya, P., and Jimenez-Gasco, M.M., which detailed a polyethylene (PE) nanocomposite integrating ethylene vinyl acetate (EVA)

and montmorillonite (MMT). This nanocomposite enhances sealability without compromising the ability to peel the seal, a feature especially beneficial for maintenance and repair scenarios of the radome.[16]

The selection of sealant materials emphasizes the need for compatibility with L-band frequency operations, prioritizing nanocomposite sealants with low dielectric constants and loss tangents to prevent signal attenuation and phase shifts. Furthermore, the sealant must exhibit robust environmental resistance to withstand the harsh conditions typical of vehicle-mounted antennas, including temperature fluctuations, UV exposure, and mechanical stresses.[25][26]

A seal that can be easily removed can be made with the EVA/MMT-based mix. This kind of seal is very important, especially for radomes that need to be taken apart and fixed often.[16]

Mixing in ethylene vinyl acetate (EVA) can lower the melting point of the basic polyethylene (PE) seal. This is useful for sealing at a lower temperature for operations. This could lower the heat pressure on the radome during making and repairing.[49]

The addition of montmorillonite (MMT) can improve mechanical properties and environmental durability of the sealant. This kind of material combination ensures the balance of environmental resistance, mechanical integrity, and radio frequency (RF) transparency[49]. This can protect the radome in environment challenge and guarantee the necessary electromagnetic properties for effective L-band signal transmission[50].

4.3.2 The exploration of hydrophilic coatings

Hydrophilic coatings are important to prevent fogging on radome surfaces. Fogging is a condition that can scatter incident light and significantly degrade the signal quality. They have self-cleaning effect by enabling water to spread and form a thin film. This can help workers wash away contaminants effortlessly.[17] Also, this property is especially beneficial for radomes positioned in unmanned tracking stations. Hydrophilic coatings can preserve the radome's transparency by ensuring that signal transmission when it comes to dirt or water streaks.[17][18]

There are two potential hydrophilic coating materials:

The first one is a surfactant-based material. While offering initial hydrophilic properties, these coatings encounter challenges such as low scratch resistance and the tendency for surfactants to leach in outdoor conditions, leading to a reduction in hydrophilicity over time. Such limitations raise concerns regarding their suitability for the radome of an L-band satellite tracking vehicle antenna, which demands consistent performance and durability.[17] 'Therefore, it can be stated, that presently surfactant-based hydrophilic coating materials are not suitable for an outdoor use, because the leaching of surfactant molecules under intensive water treatment like rain is important (loss of long time hydrophilicity).'[17]

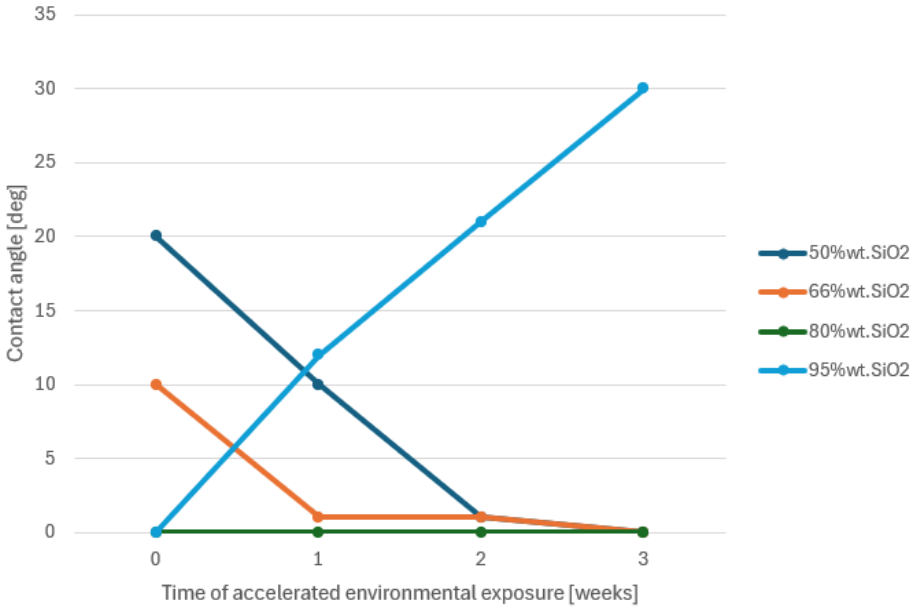


Figure 16. Contact angle measurement of SiO2 coatings after accelerated environmental exposure[17].

'As evident from the results, formulations containing 50–80%wt. SiO_2 showed improved super-hydrophilicity over time. However, hybrid formulations containing high content of nano-SiO_2 particles, (95%wt. SiO_2) that exhibited initial super-hydrophilic characteristics lost them, as the exposure to the environmental conditions was prolonged.'[17]

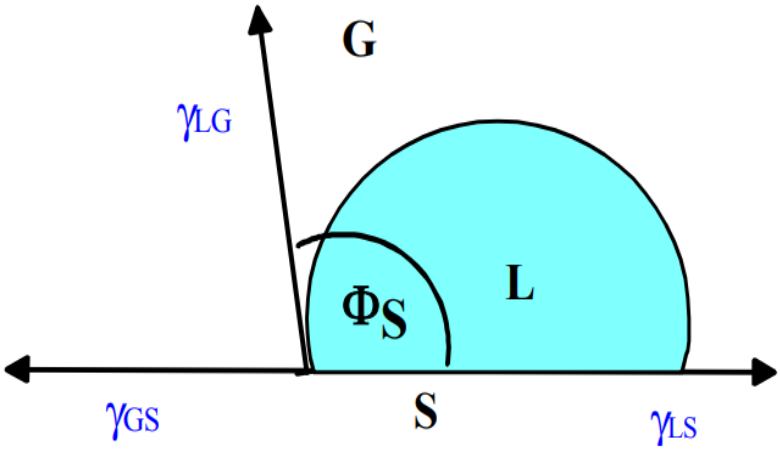


Figure 17. Wettability of a solid surface by a liquid[18].

Another potential coating is silica nanoparticle-based coatings, they are noted for their super-hydrophilicity with contact angles of less than 5°, offer high transparency and enhanced durability. 'Under static conditions, the contact angle Φ_s is used to determine the wettability of a solid material by a liquid. The smaller its value, the more a given volume of liquid spreads on a solid surface.'[18] This can be explained by (1) Young-Dupré equation:

$$\cos \Phi_s = \frac{\gamma_{GS} - \gamma_{LS}}{\gamma_{LG}} \text{ [18]} \qquad (1)$$

where Φ_S is contact angle [rad], γ_{GS} is gas–solid interfacial tension [mN/m], γ_{LS} is liquid–solid interfacial tension [mN/m] and γ_{LG} is liquid–gas interfacial tension [mN/m].

Such characteristics are essential for maintaining the signal integrity of L-band applications, making silica nanoparticle-based coatings a preferred choice for radome surfaces.[21][43]

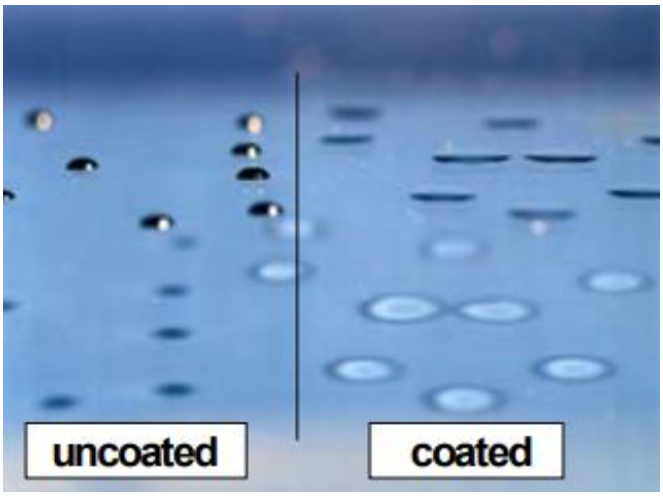


Figure 18. Water drops on a glass surface, uncoated side: hydrophobic (Φ_s= 65°) and coated side: hydrophilic (Φ_s<10°)[18].

Given the operational demands of an L-band satellite tracking vehicle antenna, including durability across environmental conditions and the imperative to maintain signal integrity, a silica nanocomposite coating containing silica nanoparticles is identified as the optimal choice. This innovative formulation combines the super-hydrophilic property imparted by silica nanoparticles with mechanical stability, courtesy of the hybrid polymer matrix.

5 Analysis

5.1 Material selection with the comparison of other materials

5.1.1 The properties of traditional materials

Table 1. Properties of the most common candidate radome materials[12].

Property	Alumina 99%	Pyroceram	Silica		Cordierite Rayceram	Silicon nitride	
			Slip cast fused	With woven quartz		Dense	Reaction bonded
Density gr. c.c.	3.9	2.6	2.2	1.8	2.45	3.2	2.4
Dielectric constant							
10 GHz 25°C	9.6	5.65	3.42	3.05	4.85	7.9	5.6
500°C	10.3	5.8	5.8	3.04	5.05	8.2	5.7
1000°C	11.4	6.1	3.8	3.02	—	—	5.8
Loss tangent							
10 GHz 25°C	0.0001	0.0002	0.0004	0.0009	0.002	0.004	0.001
500°C	0.0005	0.001	0.001	0.001	0.008	0.0045	0.0025
1000°C	0.0014	—	—	—	—	—	—
Flexural strength $N/m^2 * 10^6$							
25°C	270	235	44	—	125	400	—
500°C	250	200	54	—	120	400	—
1000°C	220	75	66	—	—	—	—
Young modulus $N/m^2 * 10^9$							
25°C	380	120	48	18	128	300	—
500°C	250	120	48	—	125	300	—
1000°C	285	100	—	—	120	—	—
Thermal shock	Fair	Good	Very good	Very good	Good	Very good	Very good
Water absorption	0%	0%	5%	20%	0%	—	20%
Rain erosion	Excellent	Very good	Poor	Poor to fair	Very good	Very good	Good

According to Table 1, the most common candidate radome materials are compared with each other. Choosing a material for the radome of an L-band satellite tracking vehicle antenna requires consideration of factors such as radio frequency (RF) transparency, mechanical properties, and environmental resistance, especially given the L-band frequency range of 1 to 2 GHz.

The weight of the radome is an essential factor, particularly for a vehicle antenna, where a lighter radome can alleviate the load on both the vehicle structure and the antenna positioning system. In this context, slip-cast fused silica, with its notably low density, emerges as a potential candidate for minimizing the overall system weight, albeit with considerations for other critical material properties.

The material’s dielectric constant and loss tangent are paramount, especially for L-band frequencies, as these properties significantly impact the material's transparency to RF signals. The data at 10 GHz can be a reference. The ideal material should have a similarly low dielectric constant and loss tangent at L-band frequencies.

The radome material should have robust mechanical properties. And the material should have the ability to withstand the stress in moving environment without distorting the RF signal. Silicon nitride has a high flexural strength at room temperature. This indicates it has good resistance to mechanical stress.

The good thermal shock resistance of Silicon nitride thermal can ensure the structural integrity of the radome under temperature fluctuations.

The presence of water can significantly change the RF characteristics of the material. Silicon nitride has zero water absorption. This means that it maintains its dielectric properties even under humid conditions.

Radome materials must be able to withstand all weather conditions, including rain erosion. Silicon nitride has very good resistance to rain erosion. This demonstrates its ability to withstand the natural environment.

Taking these factors into account, silicon nitride is the most suitable material for the radome of L-band satellite tracking vehicle antennas. It offers the best combination of L-band RF transparency and excellent mechanical properties and resistance to environmental elements. Although its density is slightly higher, this factor is not as important for vehicle systems as it is for airborne applications.

5.1.2 Comparison of fiberglass with quartz

Fiberglass is cheaper and more economical than quartz. It has good physical strength and can be flexibly combined to ensure the structural integrity and performance of the radome. Although its efficiency cannot be compared to that of quartz, it can still maintain adequate transmittance over a wide frequency range. The excellent electrical properties make glass fiber perform well in a variety of radome applications[41]. Given the long history of good structural performance of radomes made from glass fiber as a material, manufacturers are very confident in the widespread production and use of radomes, guaranteeing a stable supply of glass fiber[26].

Due to the high dielectric constant and loss angle tangent, the signal attenuation of glass fiber materials is very significant. Radomes made of fiberglass usually need thicker walls to ensure the stability of the mechanical properties[7]. This not only increases manufacturing costs, but also affects overall weight and aerodynamic performance[39].

Quartz composites have better electrical properties, like lower dielectric constant and loss angle tangent. This ensures efficient signal transmission and low signal distortion. Because quartz composites can maintain stable electrical properties over a wide temperature range, they can solve the problem of high temperatures resulting from severe aerodynamic forces. This makes them ideal for high-speed aircraft[19]. Structurally, the thickness of radomes made from quartz is usually thinner than those made from fiberglass. The quartz material is highly resistant to wear, corrosion and environmental stability. This ensures that radomes made from quartz have a long life cycle[24][27].

The disadvantages of quartz composites primarily involve their higher cost, which may deter many projects. The availability of high-quality quartz composites is limited, potentially leading to longer lead times. Quartz's brittleness may raise concerns regarding handling and durability, both during manufacturing and in use. Additionally, fabricating quartz composites can demand more specialized processes and equipment compared to fiberglass, presenting further manufacturing challenges[48][49].

5.1.3 Comparison of fiberglass with Duroid 5650

Table 2. Electrical properties of candidate radome materials[14].

Material	Dielectric Constant	Loss Tangent
Duroid 5650	2.6	0.0035
Fiberglass Epoxy (30% Resin)	4.1	0.015
Fiberglass Silicone (30% Resin)	3	0.0015
Avcoat 8027	2.9	0.03
Slip Cast Fused Silica (SCFS)	3.33	0.004
Fiberglass Epoxy (18% Resin)	5	0.015
Fiberglass Silicone (18% Resin)	5	0.006

Table 2 shows the comparison of fiberglass (with varying resin content) with Duroid 5650, examining their suitability as radome materials based on their dielectric properties.

From dielectric Constant and Loss Tangent perspective, the dielectric constant is a measure of a material's ability to store electrical energy in an electric field. Lower values are generally preferable for radome materials to ensure that the radar waves can pass through the material with minimal reflection and refraction. Duroid 5650 boasts a dielectric constant of 2.6, making it an excellent candidate for radomes. It sits lower than both fiberglass epoxy (30% resin) and fiberglass silicone (30% resin), which have dielectric constants of 4.1 and 3.0, respectively. Notably, the fiberglass variants with 18% resin content have even higher dielectric constants of 5.0, which might not be ideal for high-frequency radar applications where wave interaction with the radome material should be minimized.[7]

Considering the loss tangent, another critical parameter, quantifies the material's inherent dissipation of electromagnetic energy. It is a direct indicator of how much signal loss occurs due to the material itself. Duroid 5650 has a low loss tangent of 0.0035, indicating that it would allow for efficient signal transmission with minimal energy loss[45]. The fiberglass materials, in comparison, show higher loss tangents across the board. Specifically, fiberglass epoxy (30% resin) has a loss tangent of 0.0150, and the silicone variant (30% resin) has 0.0015, indicating that while fiberglass silicone has comparatively lower energy dissipation, it is still not as efficient as Duroid 5650. Furthermore, increasing the resin content in

fiberglass materials to 18% also increases the loss tangent to 0.015 for epoxy and 0.006 for silicone, which further hampers their performance in comparison to Duroid 5650.[7]

Duroid 5650 emerges as a superior material for radome applications when considering dielectric properties alone, with its lower dielectric constant and loss tangent ensuring better electromagnetic transparency. However, the choice between Duroid 5650 and fiberglass may ultimately depend on a trade-off analysis between electromagnetic performance and mechanical robustness. For radar systems where signal integrity is paramount, Duroid 5650 would likely be the preferred choice[7]. In contrast, applications that demand high mechanical strength might benefit from the customizable properties of fiberglass, despite its higher dielectric constant and loss tangent[26][39].

5.1.4 Comparison of fiberglass with acrylic (AC)

Traditionally, fiberglass has been utilized for its structural integrity and cost-effectiveness[26]. However, as satellite tracking advances toward more precise and higher-frequency bands like L-band (1 to 2 GHz), the demand for materials with superior electromagnetic properties intensifies[3][9]. Acrylic, known for its favorable dielectric characteristics at these frequencies, emerges as a competitive alternative[47][48].

Fiberglass radomes boast significant mechanical strength and resilience, which are essential for the mobile nature of satellite tracking vehicles[26]. The material's dielectric properties, notably in the L-band range, offer adequate performance where high penetration depth and lower dielectric losses are less critical[6]. Nonetheless, the dielectric constant and loss tangent of fiberglass may vary based on resin content, potentially impacting the antenna's radiation pattern[39].

Acrylic offers a lower dielectric constant and loss tangent, suggesting reduced signal attenuation and reflection, thus enhancing the antenna's performance. Its stability across a wide frequency spectrum makes it an attractive option for L-band applications, where consistent electromagnetic behavior is required for optimal signal transmission and reception[10].

Comparing dielectric constant and loss tangent, in the L-band frequency, acrylic's lower dielectric constant translates to a reduced phase shift of the transmitted signal, enhancing the tracking antenna's ability to maintain signal coherence[46]. Fiberglass, with a higher dielectric constant, might necessitate additional design considerations to mitigate any adverse effects on the antenna's beamwidth and sidelobe levels.

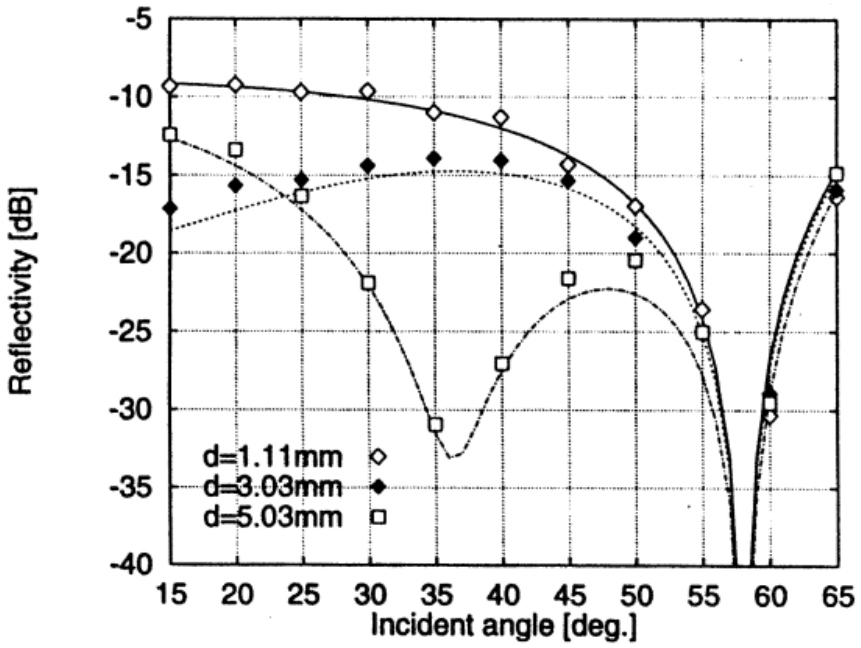
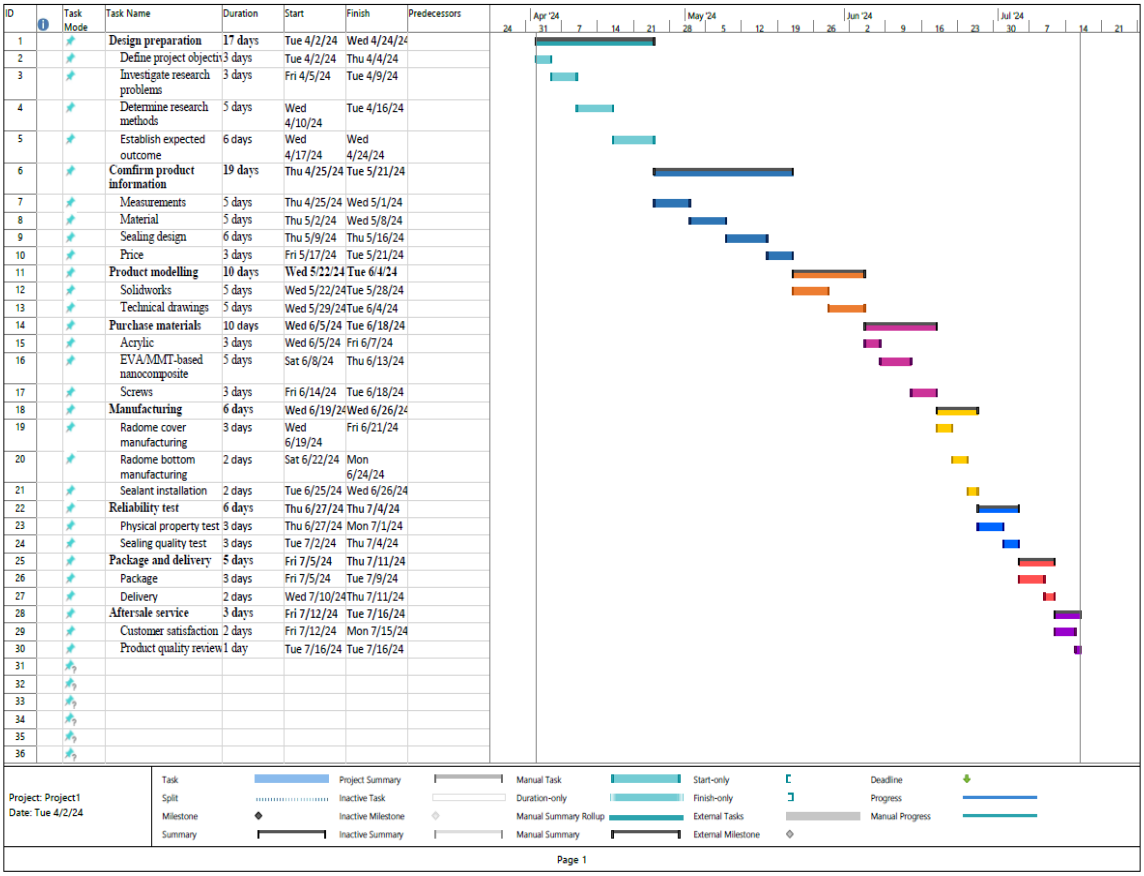


Figure 19. Measured and calculated results of reflectivity (for AC)[15].

The displayed data in Figure 19 compare the reflectivity of acrylic at different thicknesses—1.11 mm, 3.03 mm, and 5.03 mm—across a spectrum of incident angles pertinent to L-band satellite tracking antennas. Thinner acrylic exhibits lower reflectivity variance with angle, making it favorable for radome use where signal consistency is critical. The 5.03 mm thickness shows a minimum reflectivity at mid-range angles but a sharp increase past 55°, indicating potential signal inconsistencies at steeper incident angles. Optimal acrylic thickness for an L-band antenna radome would, therefore, balance minimal reflectivity with mechanical requirements, suggesting thinner acrylic may be preferred for consistent L-band signal transmission[8].

5.2 Manufacturing plan

Figure 20 is a Gantt chart clearly presents the manufacturing plan of the radome. The manufacturing plan includes design preparation, confirm product information, product modelling, purchase materials, manufacturing, reliability test, package and delivery, aftersale service.



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Design preparation**	**17 days**	Tue 4/2/24	Wed 4/24/24	
2		Define project objectiv	3 days	Tue 4/2/24	Thu 4/4/24	
3		Investigate research problems	3 days	Fri 4/5/24	Tue 4/9/24	
4		Determine research methods	5 days	Wed 4/10/24	Tue 4/16/24	
5		Establish expected outcome	6 days	Wed 4/17/24	Wed 4/24/24	
6		**Comfirm product information**	**19 days**	Thu 4/25/24	Tue 5/21/24	
7		Measurements	5 days	Thu 4/25/24	Wed 5/1/24	
8		Material	5 days	Thu 5/2/24	Wed 5/8/24	
9		Sealing design	6 days	Thu 5/9/24	Thu 5/16/24	
10		Price	3 days	Fri 5/17/24	Tue 5/21/24	
11		**Product modelling**	**10 days**	**Wed 5/22/24**	**Tue 6/4/24**	
12		Solidworks	5 days	Wed 5/22/24	Tue 5/28/24	
13		Technical drawings	5 days	Wed 5/29/24	Tue 6/4/24	
14		**Purchase materials**	10 days	Wed 6/5/24	Tue 6/18/24	
15		Acrylic	3 days	Wed 6/5/24	Fri 6/7/24	
16		EVA/MMT-based nanocomposite	5 days	Sat 6/8/24	Thu 6/13/24	
17		Screws	3 days	Fri 6/14/24	Tue 6/18/24	
18		**Manufacturing**	**6 days**	Wed 6/19/24	Wed 6/26/24	
19		Radome cover manufacturing	3 days	Wed 6/19/24	Fri 6/21/24	
20		Radome bottom manufacturing	2 days	Sat 6/22/24	Mon 6/24/24	
21		Sealant installation	2 days	Tue 6/25/24	Wed 6/26/24	
22		**Reliability test**	**6 days**	Thu 6/27/24	Thu 7/4/24	
23		Physical property test	3 days	Thu 6/27/24	Mon 7/1/24	
24		Sealing quality test	3 days	Tue 7/2/24	Thu 7/4/24	
25		**Package and delivery**	**5 days**	Fri 7/5/24	Thu 7/11/24	
26		Package	3 days	Fri 7/5/24	Tue 7/9/24	
27		Delivery	2 days	Wed 7/10/24	Thu 7/11/24	
28		**Aftersale service**	**3 days**	Fri 7/12/24	Tue 7/16/24	
29		Customer satisfaction	2 days	Fri 7/12/24	Mon 7/15/24	
30		Product quality review	1 day	Tue 7/16/24	Tue 7/16/24	
31						
32						
33						
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35						
36						

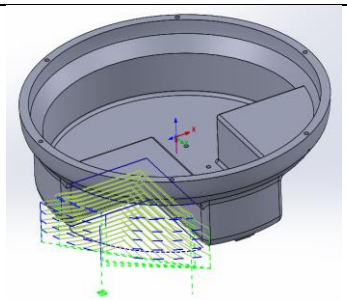
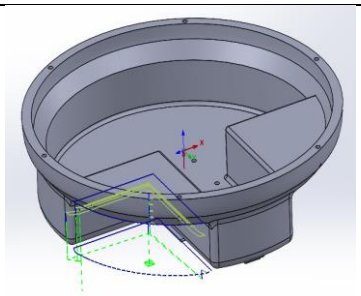
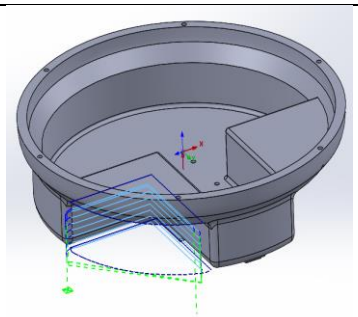
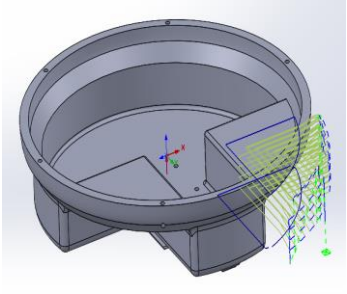
Figure 20. Gantt chart of manufacturing plan.

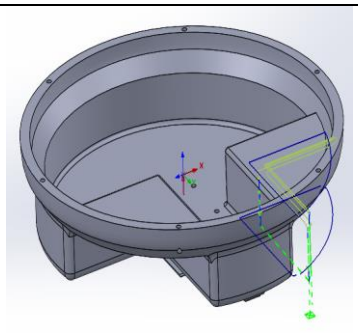
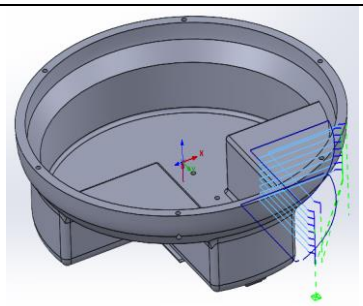
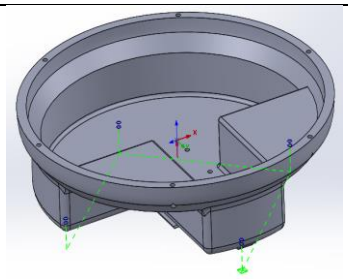
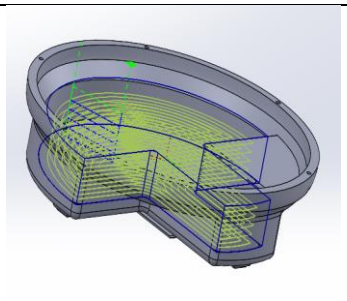
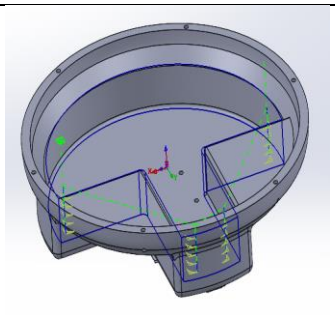
5.3 CAM simulation

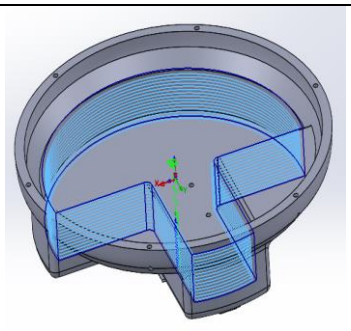
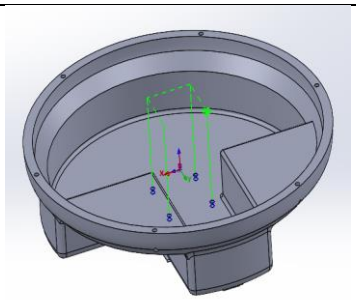
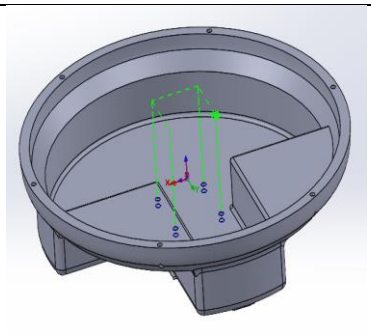
CAM is a SolidWorks function used to simulate the processing of workpieces by CNC machining centers. Through the CAM function, the manufacturing process of products can be simulated to ensure the machinability of product.

In this radome design, it is particularly critical to perform CAM analysis due to its complex shape and features. The following table describes how the structure of the radome bottom is manufactured during the actual machining process. This simulation uses a 5-axis Milling machining center.

Table 3. CAM simulation procedure.

Machining stage	Geometry	Simulated time	% (of total time)
Rough mill 1		13.387min	14.977%
Rough mill 2		1.407min	1.574%
Contour mill 1		1.850min	2.070%
Rough mill 3		12.835min	14.359%

Rough mill 4		1.372min	1.535%
Contour mill 2		1.809min	2.024%
Drills		0.922min	1.031%
Rough mill 5		44.337min	49.602%
Rough mill 6		2.475min	2.769%

Contour mill 3		8.890min	9.946%
Center mill		0.102min	0.114%
Center drill		0.111min	0.124%

6 Discussion

The design for the radome of L-band satellite tracking vehicle antennas is at the forefront of addressing key challenges in satellite communication technology. This research embarked on an in-depth analysis and selection of materials and sealing techniques that enhance the performance, durability, and operational reliability of antenna radomes, which are crucial for maintaining high-quality satellite communications.

6.1 Material selection and design considerations

Acrylic is chosen as the material for the radome. A comprehensive evaluation of dielectric properties, environmental resistance, and manufacturability is considered when choosing the material.

Acrylic emerged as superior primarily due to its excellent dielectric properties, which ensure minimal signal attenuation. It also has outstanding mechanical durability and resistance to environmental factors such as UV exposure, temperature variations, and physical impacts. Therefore, it is highly suitable for the demanding operational environment of satellite tracking vehicle antennas.

This thesis also studied the limitations of traditional materials like fiberglass. The fiberglass has certain benefits, including mechanical strength and cost-effectiveness. But it also has higher dielectric constant and loss tangent. The study also compares the properties of fiberglass with some modern materials, including acrylic and Duroid 5650. This shows the advantages of modern polymers and composites.

The material selection is a big concern because it highly related to the performance of the antenna inside the radome. The signal of the antenna should transmit through the radome which means every signal can not avoid passing through the radome. Therefore, it is clear that the radome is very important in the radome design.

6.2 Sealing solutions and hydrophilic coatings

This study finds nanocomposite sealants as an innovative sealing solution for radomes. The sealant also has excellent compatibility with L-band frequency.

The study further investigated the application of hydrophilic coatings, particularly silica nanoparticle-based coatings. It can prevent fogging on radome surfaces and maintain signal integrity. This innovative solution improves the radome's performance.

This method to solve the sealing problem of the radome is an innovative design. From the previous studies, the performance of nanocomposite is outstanding. There are also a wide range of nanocomposites which can be utilized as the sealant of the radome. This makes the application of nanocomposites easier and more efficient.

In addition to the nanocomposites applied, the application of hydrophilic coatings is also very important. The nanocomposites can fill the tiny gaps between the upper and lower parts of the radome and can seal the radome very well. However, if the operational environment of the radome gets wet or erosive, it is important to prevent the nanocomposite from aging. The layer of hydrophilic coatings can form a very tight and waterproof film which can transform the water or fogging on the surface into a film. This can avoid interfering with the signal transmission of the antenna as well as protect the nanocomposites from erosion.

6.3 SolidWorks modelling and technical drawings

Some dimensions are strictly standardized in a design, such as flange joints, waveguide sizes, connector fastenings, therefore some of those cannot be changed. For this radome design, it is clear that the diameter of fillets, the diameter of screws should remain the same.

After having recognized the most time-consuming manufacturing stage it is possible to find ways and focus to make that stage easier or quicker. It is possible to change the optimized material combination between the tooling and device materials. According to 5.3, the CAM simulation in SolidWorks indicates that the most time-consuming process is rough mill 5, which takes 44.337min. This is mainly due to the high and wide dimensions of the parts which need to be cut off from the original material. In addition to that, the 5-axis milling

machining center may also be relatively inefficient because of its complicated operational feature. 5-axis milling machining center is highly suitable for structurally complicated and dimensionally strict model, for example some medical devices, automotive parts, aerospace components. For the radome discussed in this thesis, it is clear that the material properties and the sealing solutions are more important and stricter than the tolerance of the model. The tolerance is not highly considered in manufacturing process since the dimensions are not a big concern, which means a little bit bigger or smaller than expected is acceptable and should not cause any problem to the operation of antenna inside the radome.

7 Summary

This thesis gives new ideas to the design and construction of radomes for L-band satellite tracking vehicle antennas. It identifies acrylic as a superior material for radome construction. It also introduces nanocomposite sealants and hydrophilic coatings for enhanced sealing. This research offers innovative solutions to improve the performance and longevity of antenna radomes and a systematic method to improve satellite communication technology. It sets a new standard for future research on using new materials and methods in radome design, which could help improve satellite communication systems even more.

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